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# The IOVP effect in mindless reading: Experiment and modeling

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**Abstract**

Fixation durations in reading are longer for within-word fixation positions close to word center than for positions near word boundaries. This counterintuitive result was termed the Inverted-Optimal Viewing Position (IOVP) effect. We proposed an explanation of the effect based on error-correction of mislocated fixations [Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research,* 45, 2201–2217], that suggests that the IOVP effect is not related to word processing. Here we demonstrate the existence of an IOVP effect in "mindless reading", a *z*-string scanning task. We compare the results from experimental data with results obtained from computer simulations of a simple model of the IOVP effect and discuss alternative accounts. We conclude that oculomotor errors, which often induce mislocalized fixations, represent the most important source of the IOVP effect.


*Keywords:* Reading; Saccades; Optimal viewing position; Oculomotor errors; Mislocated fixations

## 1. Introduction

During reading, the word center (i.e., the *optimal viewing position*) appears to be the optimal fixation location to process a word efficiently (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989, for continuous reading; O'Regan & Lévy-Schoen, 1987, for isolated word recognition). Counter to this expectation, however, Vitu, McConkie, Kerr, and O'Regan (2001) reported the surprising discovery that fixation durations are longer for words fixated close to the word center than for cases where the fixation location is close to word edges. This phenomenon, introduced as the fixation-duration Inverted-Optimal Viewing Position (IOVP) effect, has received considerable attention, because it is recognized as an important limitation of theoretical models of eye-movement control during reading (for latest installments see Engbert, Nuthmann, Richter, & Kliegl, 2005; McDonald, Carpenter, & Shillcock, 2005; Pollatsek, Reichle, & Rayner, 2006).

We introduced an explanation for the IOVP effect, based on a computational algorithm linking the effect to mislocated fixations, i.e. to fixations on unintended words (Nuthmann, Engbert, & Kliegl, 2005), and implemented the proposed mechanism in the SWIFT model of saccade generation during reading (Engbert et al., 2005; Engbert, Nuthmann, & Kliegl, 2007). In addition to the SWIFT model, two other computational models are now able to reproduce aspects of the IOVP effect: the latest version of the E-Z Reader model (Pollatsek et al., 2006) and the SERIF model (McDonald et al., 2005). Furthermore, the discoverers of the IOVP effect propose a *perceptual economy account* and discuss several visuo-motor hypotheses (Vitu et al., 2001). Here, we provide further evidence on the link between the IOVP effect and error correction of mislocalized fixations (Nuthmann et al., 2005) and test predictions derived from the SERIF model (McDonald et al., 2005) as well as the perceptual-economy hypothesis (Vitu et al., 2001).

In the experiment, participants read German sentences in both their normal version (e.g., Nach der Trauung wartete eine Kutsche vor der Kirche.) as well as a "mindless"

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version (e.g., Zzzz zzz Zzzzzzz zzzzzzz zzzz Zzzzzzz zzz zzz Zzzzzz). In the following, hypotheses about the IOVP effect are developed in detail. Finally, predictions with regard to the *z*-string data are derived.

### *1.1. IOVP effect: mislocalization explanation*

Our own IOVP model expands on the consequences of oculomotor errors which produce—when large enough—mislocated fixations (cf., McConkie, Kerr, Reddix, & Zola, 1988). The theoretical claim is that a new, potentially corrective, saccade program is started instantaneously if the intended target word is missed. How can error-correcting responses to mislocated fixations generate an IOVP effect?

First, the proposed mechanism implies that the oculomotor system is able to recognize whether the eye landed on the intended target word or not. Saccade amplitudes are determined by population-coded activations in the superior colliculus (e.g., Sparks, 2002, for a review). Accordingly, saccades are controlled by an efference copy of the motor signal to the eye muscles (Carpenter, 2000; Wurtz, 1996; see also Bergeron, Matsuo, & Guitton, 2003). Consequently, gaze error is continuously monitored during saccades, which potentially provides a very fast detection of saccade errors. From these considerations, it is neurophysiologically plausible that a new saccade program can be started at the beginning of the mislocalized fixation, if the intended target word is missed. We thus assume that gaze error information is available not only in terms of the magnitude of saccadic error but also in terms of whether the eyes landed on the intended target word (i.e., a low-spatial frequency blob) or not.

Second, the immediate start of a new saccade program leads to shorter durations for mislocated fixations. In models of eye-movement control in reading it is commonly assumed that in the majority of cases, the program for the next saccade is initiated during the time course of the current fixation (e.g., Reichle, Rayner, & Pollatsek, 2003). Consequently, the assumption of error-correcting saccade programs being started at or close to the beginning of the mislocated fixation will lead, on average, to decreased durations for mislocated fixations as opposed to well-located fixations (see Engbert et al., 2007, for simulations). Importantly, a reduced duration for mislocated fixations does not imply a reduced programming time for saccades following mislocated fixations. Third, because mislocated fixations were shown to be most prevalent at the beginning and end of words (Nuthmann et al., 2005), the proposed mechanism generated the inverted U-shape for fixation durations when computed as a function of landing position.

Taken together, we proposed that the IOVP effect is caused by oculomotor mechanisms, and hence is unrelated to word recognition processes. The latter hypothesis is supported by the observation that the word frequency effect on fixation durations is largely independent of landing position: Fixation durations are longer for low-frequency than for high-frequency words (Nuthmann et al., 2005; Vitu et al., 2001; see also Rayner, Sereno, & Raney, 1996, but reporting a non-significant effect of landing position).

The relation between mislocated fixations and the IOVP effect, as developed in Nuthmann et al. (2005), was implemented in the SWIFT model (Engbert et al., 2005; Engbert et al., 2007). In the SWIFT model, it is suggested that words are processed in parallel and that target selection is a stochastic process based on the relative strength of activations of words. In such a model, mislocated fixations are simply an additional source of stochasticity without dramatic consequences for word processing. Furthermore, the mechanism of error-correcting saccades will not automatically lead to a correction of unintended landing positions because target selection in SWIFT is inherently autonomous and stochastic (Engbert, Longtin, & Kliegl, 2002; Engbert & Kliegl, 2003a; Engbert, Kliegl, & Longtin, 2004; Richter, Engbert, & Kliegl, 2006). Because processing of words is spatially distributed over several words at a time, error corrections will turn out to be unnecessary in a certain fraction of cases (for details see Engbert et al., 2007).

### *1.2. IOVP effect: alternative explanations*

There are two alternative explanations for the IOVP effect in other computational models (SERIF, E-Z Reader), and there is an alternative perceptual-economy account based on experimental research.

#### *1.2.1. SERIF*

The SERIF model centers on the suggestion that a vertically split fovea and the projection of information in either visual field to the contralateral hemisphere have consequences for eye-movement control in reading (McDonald et al., 2005). The IOVP effect is attributed to the independent accumulation of information in the two hemifields coupled with a lateral inhibition mechanism between two saccadic decision units (cf., LATER model, Carpenter, 1981; Carpenter & Williams, 1995). The effect emerges because lateral inhibition (i.e., competition between the two LATER units) is stronger at word center as compared to word edges.

#### *1.2.2. E-Z Reader*

The E-Z Reader model (Pollatsek et al., 2006) generates the effect for the first of two fixations as a consequence of the model's assumptions on refixation behavior. First, the probability of initiating a refixation saccade is directly proportional to the distance between the initial fixation location on a word and its center (cf., McConkie et al., 1989). Second, the completion of $L_1$, the first stage of lexical access, causes the oculomotor system to program a saccade to the next word. Usually, $L_1$ takes less time to complete for fixations located at word center. In this case, the refixation saccade is most likely to be cancelled. Thus, refixation saccades starting from word center only occur in cases where $L_1$ takes a long time to complete. This bias inflates the first of two fixations for initial fixations located near the center of a word. E-Z Reader 9, however, cannot reproduce the characteristic trade-off effect for two-fixation cases (Engbert et al., 2005; O'Regan & Lévy-Schoen, 1987; Vitu et al., 2001) with the second fixation being shortest, rather than longest, at word center when second fixation duration is plotted conditional upon the position of the first fixation. In addition, the IOVP effect observed in single-fixation durations is still a challenge for the model.

#### 1.2.3. Perceptual economy

Aside from these explanations originating in computational-modeling research, there are further hypotheses originating in experimental research. According to Vitu et al. (2001), the IOVP effect is due to a *perceptual economy strategy* principle: Based on reading experience, the perceptuo-oculomotor system learns to produce longer fixations at the central region of a word because here, greater information is anticipated (see also Vitu, Lancelin, & Marrier d'Unienville, submitted for publication). Finally, the authors consider several visuo-motor hypotheses; the basic idea is that, due to low-level visuo-motor constraints associated with saccade programming, it takes longer to program a saccade from the center of a stimulus (e.g., a word) as compared to the edges of the stimulus.

In the SERIF model (McDonald et al., 2005), two saccadic decision units, representing the two hemispheres, control intersaccadic intervals via linear rises of activation. The mean rise rate parameter $\mu$ is related to the frequency of the currently fixated word (Eq. 2a). For each hemispheric LATER unit, $\mu$ is additionally a function of "information content" which broadly corresponds to the statistical properties of the letter sequences in a word (Eqs. 3a and 3b in McDonald et al., 2005). Thus, the rise rates for activations are related to word frequency and information content, but not to low-level stimulus features (e.g., length of letter strings, shape or size of stimuli). Consequently, the SERIF model would predict a strongly reduced IOVP effect for meaningless letter strings.

Similarly, the perceptual-economy explanation assumes that there is information to be processed (Vitu et al., 2001). According to this explanation, longer fixations at word centers are a consequence of statistically acquired knowledge about optimal strategic behavior. Longer fixations at word centers are of no advantage in *z*-string reading. Therefore, if readers are able to flexibly adjust their scanning strategies, the IOVP effect should be considerably reduced or even absent in *z*-string reading. On the other hand, if readers employ the same perceptual-economy strategies as in normal reading, an IOVP effect of a similar size as in normal reading would be predicted.

### 1.3. Mindless reading

#### 1.3.1. Paradigm

To test our mechanism for the IOVP effect based on mislocalized fixations (Nuthmann et al., 2005) against the anatomical explanation (McDonald et al., 2005) as well as the perceptual-economy hypothesis (Vitu et al., 2001), we carried out a study on "mindless reading" as an oculomotor control condition to normal reading. In this paradigm (Vitu, O'Regan, Inhoff, & Topolski, 1995), all letters in a text are replaced with *z*s (in the following, *z*-strings) while punctuation and spacing are preserved. Participants are instructed to scan the text as if they were reading. Consequently, the paradigm is frequently termed *mindless reading*. Results by Vitu et al. (1995) indicated that the global characteristics of saccades are quite similar for *z*-string reading and normal reading (but see Fischer, 1999; Rayner & Fischer, 1996, for differences in saccade control between these tasks). Thus, reading of *z*-strings may provide useful information about oculomotor processes typical of normal reading in the absence of word processing.

#### 1.3.2. Predictions

According to our theoretical explanation, the IOVP effect is due to low-level oculomotor mechanisms, and hence is unrelated to word recognition. Thus, finding a fixation-duration IOVP effect in *z*-string reading would strongly support our theory that error-correction of mislocalized fixations generates the effect.

## 2. Methods

### 2.1. Participants

Twenty-six university students (16 women and 9 men, 1 n.a.; mean age = 22.4 years, SD = 2.3 years) participated in the experiment. They received either course credit or a payment of 5€. All participants were native German readers and had normal or corrected-to-normal vision.

### 2.2. Apparatus, materials and procedure

Participants attended two sessions at different days. In one session, they read the 144 sentences of the Potsdam Sentence Corpus (Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006) comprising 1138 words. Excluding the first word of each sentence which was not used in the analyses, frequencies of word lengths 3–8 were: 222, 134, 147, 129, 92, 72. In the other session, participants read the *z*-string version of the PSC. *Z*-string sentences were created by replacing all letters of the alphabet with the letter *z*, preserving inter-word spaces, punctuation, and letter cases. Consistent with Vitu et al. (1995), participants were instructed to pretend that they were reading each line of *z*-strings. We tried to prime normal reading behavior by presentation of normal filler sentences: The *z*-string trials were randomly mixed with 36 normal sentences. Session order was randomized. Compared to the present study, both Vitu et al. (1995) as well as Rayner and Fischer (1996) employed somewhat different designs. Note that Rayner and Fischer (1996) presented normal and *z*-transformed sentences either in a randomized or in a blocked sequence. Importantly, the presentation order manipulation did not affect fixation durations in *z*-string scanning.

Participants were tested with a SR Research EyeLink II System with a sampling rate of 500 Hz. Calibrated eye position was recorded accurately at the level of letters. Saccade detection was performed using an algorithm introduced by Engbert and Kliegl (2003b, updated by Engbert and Mergenthaler, 2006). For further details on materials, experimental procedure, and data selection see Kliegl et al. (2004, 2006). Computations for participant-based landing position distributions and IOVP curves per word/ string length were based on all reading fixations on 3–8-letter words, except the first and last fixations in a sentence as well as fixations being shorter than 30 ms and longer than 1000 ms. For analyses, landing positions were standardized by dividing the letter position by word length, yielding values between 0 (i.e., for fixations on the space before the word) and 1.

## 3. Results

### 3.1. Global analyses

Fixation durations were significantly longer ($M=245$ ms, $SD=38$ ms vs. $M=203$ ms, $SD=22$ ms) in $z$-string than in normal reading ($F(1,25)=41.2$, $MSe=598.3$, $p<.001$). Fig. 1a displays the corresponding mean frequency distributions. Proportion of fixation durations is displayed for 20 levels (from 30 ms up to 600 ms in 30-ms steps). The fixation duration distribution for $z$-strings is clearly shifted to the right which lends further support to the finding that participants produced longer fixation durations when engaged in mindless reading (Rayner & Fischer, 1996; Vitu et al., 1995).

Means (standard deviations) for forward saccades were 7.8 (2.8) and 7.1 (1.2) letters for $z$-string and normal reading. Consistent with prior research, mean length of forward saccades did not differ between the two conditions ($F(1,25)=2.0$, $MSe=2.9$, $p=.174$). Mean length of regressive saccades was −4.0 (1.9) and/or −6.2 (2.2) letters with the difference being significant ($F(1,25)=31.4$, $MSe=2.0$, $p=.000$). The corresponding mean frequency distributions are bimodal (Fig. 1b), with negative saccade lengths indicating regressive saccades. Readers perform regressions less frequently during reading of $z$-strings than during normal reading. In addition, the proportion of short forward saccades (1–5 letters) as well as very long forward saccades ($\geqslant 15$ letters) is higher when scanning $z$-strings than when reading normal sentences; the opposite is true, however, for medium-long saccades. This finding is roughly compatible with a lower skipping rate for short $z$-strings (as opposed to short words) and higher skipping rate for long $z$-strings (Nuthmann, 2006; Vitu et al., 1995).

### 3.2. Preferred viewing location (PVL)

We proposed that the fixation-duration IOVP effect is due to error correction of mislocated fixations (Nuthmann et al., 2005). The probability of these mislocated fixations is estimated from the overlap of empirical landing position distributions between neighboring words. Landing position distributions for words of a given length are approximately normal in shape, with the mean falling slightly left of word center (i.e., the *Preferred Viewing Location*, Rayner, 1979).

An empirical PVL curve was computed for each participant and each word/ string length from 3 to 8 letters, and normal curves were fitted to these data. Mean and standard deviation of the best-fitting normal curve determine the PVL curve. To obtain estimates for both parameters, a grid search method with a minimum-$\chi^2$ criterion was applied. For proportions, means and standard deviations, values were averaged across participants. Landing position distributions are very similar for $z$-string reading vs. normal reading data (Fig. 2, descriptive statistics: Table 1).

Neither means $M'$ ($F(1,25)=0.014$, $MSe=0.042$, $p=.908$) nor standard deviations $SD$ ($F(1,25)=3.0$, $MSe=2.418$, $p=.095$) of the Gaussian landing position

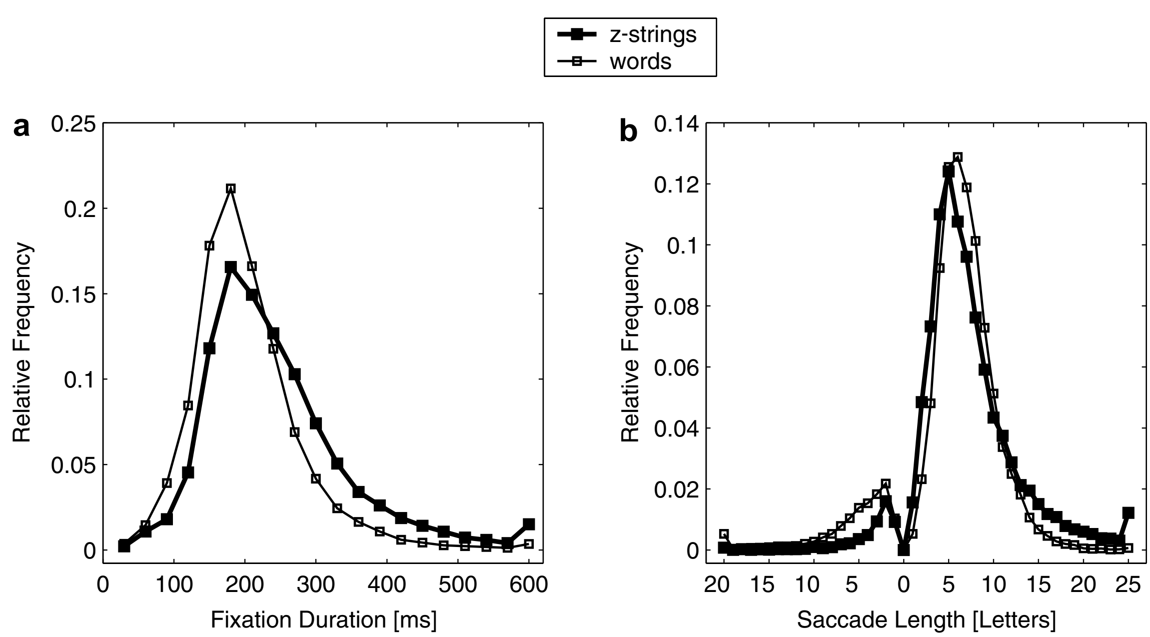


Fig. 1. Global analyses. (a) Distribution of all observed fixation durations during $z$-string reading (full squares) vs. normal reading (open squares). (b) Distribution of all observed saccade lengths.

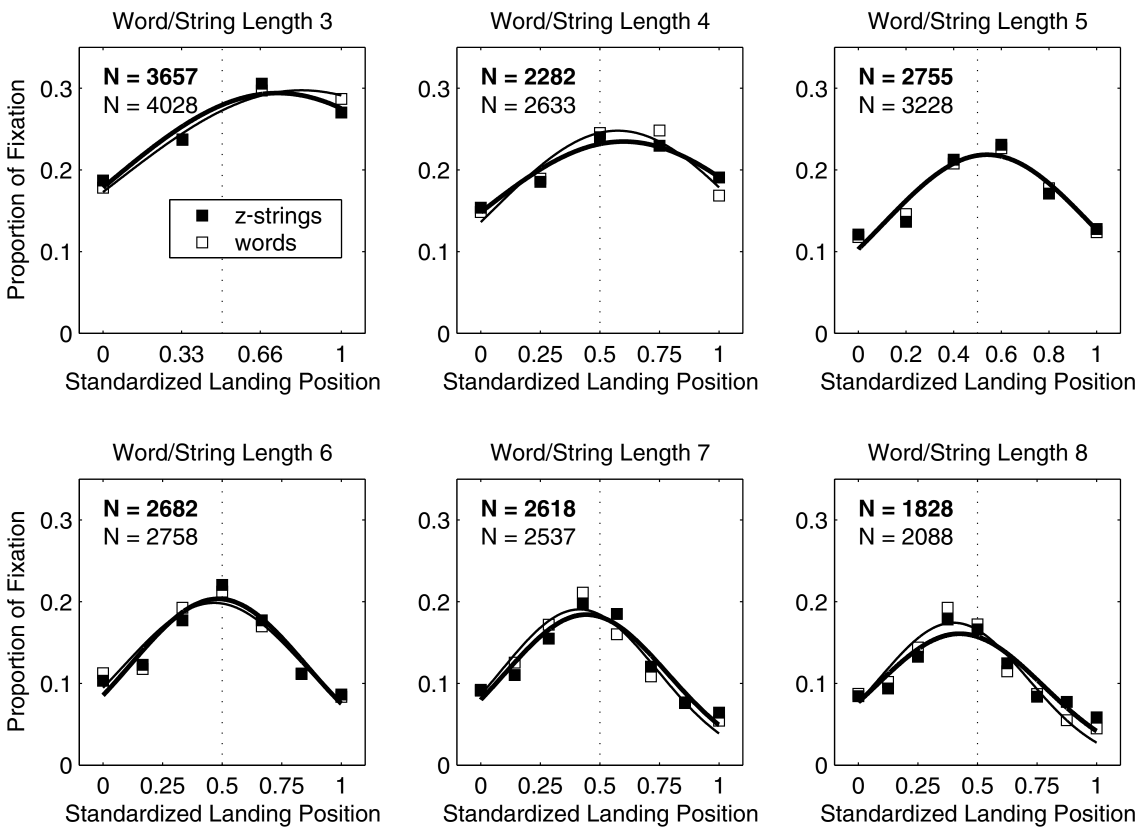


Fig. 2. Landing position distributions. Comparison of $z$-string reading data (full squares) with normal reading data (open squares) as a function of word/string length. Each panel represents data for a given word/string length (3 through 8). Also presented is the best-fitting normal curve for each distribution.

Table 1
Normal fit to landing position distributions for $z$-string reading data vs. normal reading data: Estimates of parameters $M$, $M_C$, $M'$ and $SD$ for words/$z$-strings of a given length

| Word length | Center of word | $z$-string reading | | | | | Normal reading | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $M$ | $M_C$ | $M'$ | $SD$ | $\chi^2$ | $M$ | $M_C$ | $M'$ | $SD$ | $\chi^2$ |
| 3 | 2 | 2.14 | 0.14 | 0.71 | 2.18 | 0.00272 | 2.32 | 0.32 | 0.77 | 2.05 | 0.00485 |
| 4 | 2.5 | 2.5 | 0 | 0.63 | 2.49 | 0.00783 | 2.42 | −0.08 | 0.6 | 2.27 | 0.00702 |
| 5 | 3 | 2.73 | −0.27 | 0.55 | 2.65 | 0.00655 | 2.9 | −0.1 | 0.58 | 2.38 | 0.00446 |
| 6 | 3.5 | 2.99 | −0.51 | 0.5 | 2.69 | 0.00861 | 3.01 | −0.49 | 0.5 | 2.54 | 0.00785 |
| 7 | 4 | 3.02 | −0.98 | 0.43 | 2.79 | 0.00903 | 2.8 | −1.2 | 0.4 | 2.47 | 0.00958 |
| 8 | 4.5 | 3.44 | −1.06 | 0.43 | 3.28 | 0.01205 | 3.21 | −1.29 | 0.4 | 2.55 | 0.01017 |

*Note.* $M_C = M$—center of word. $M' = M$/word length. $\chi^2$ denotes sum of squared residuals.

distributions differed when reading of $z$-strings was compared with normal reading in two $2 \times 6$ repeated measures ANOVAs with experimental condition and word length as within-subject factors. There was, however, a significant word length effect for both $M'$ ($F(5,21) = 35.5$, $MSe = 0.047$, $p < .001$) and $SD$ ($F(5,21) = 4.03$, $MSe = 1.441$, $p = .009$) not interacting with the experimental condition. These results are in agreement with earlier research reporting no reliable differences in landing positions between $z$-string reading and normal reading (Rayner & Fischer, 1996; Vitu et al., 1995, although applying a completely different analysis scheme). Thus, where the eyes land in a word does not seem to reflect higher levels of processing.

### 3.3. Inverted-Optimal Viewing Position (IOVP) effect for fixation durations

As shown in Fig. 3, $z$-string reading yielded very clear IOVP curves. For each participant, six empirical fixation-duration IOVP curves were fitted for word/string lengths 3–8 using a quadratic polynomial as reference curve, i.e.

$$y = A - B(x - C)^2, \tag{1}$$

where $x$ denotes the fixation position and $y$ is the fixation duration. In Eq. (1), $C$ represents the fixation position of maximum fixation duration. As shown earlier (Nuthmann et al., 2005), parameter $C$ is roughly equivalent to the optimal viewing position (OVP), which can be computed from

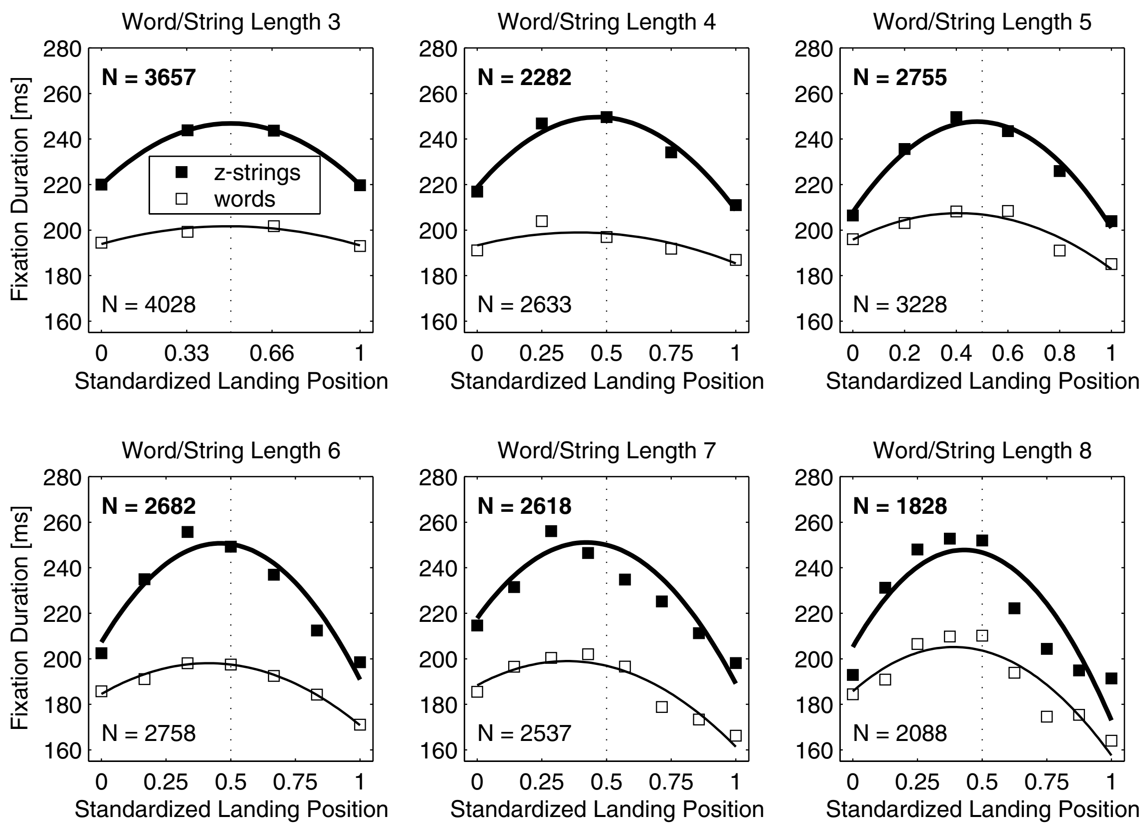


Fig. 3. Fixation-duration IOVP effect: mean fixation duration as a function of standardized landing position within a word/string. Comparison of *z*-string reading data (full squares) vs. normal reading data (open squares). Each panel represents data for a given word/string length (3–8). Lines represent best fits to a second-order polynomial (see text for details).

the location of minimum refixation probability. Parameter $A$ indicates the maximum fixation duration at OVP. Mathematically, $A$ and $C$ reflect the vertical and/or horizontal offset of the curve, respectively. $B$ is the slope of the parabolic curve; it represents how fixation duration decreases with deviation from OVP, that is $B$ quantifies the "benefit" for not fixating at OVP. The fits were based on standardized landing positions. Note that this standardization was compensated by a transformation of parameters $B$ and $C$ to $B' = B \cdot L^2$ and $C' = C/L$.

Parameters $A$, $B'$, and $C'$ of the fitted quadratic function describe the fixation-duration IOVP effect. Parameters $A$ and $B'$ are considerably larger in *z*-string reading than in normal reading (Fig. 4 and Table 2). For each of the three parameters, a $2 \times 6$ repeated measures ANOVA with experimental condition and word length as within-subject factors was conducted. As suggested by Fig. 4, both $A$ ($F(1,25) = 31.76$, $MSe = 5673$, $p = .000$) as well as $B'$ ($F(1,25) = 21.18$, $MSe = 34305$, $p = .000$) were significantly larger in *z*-string than in normal reading. There were also

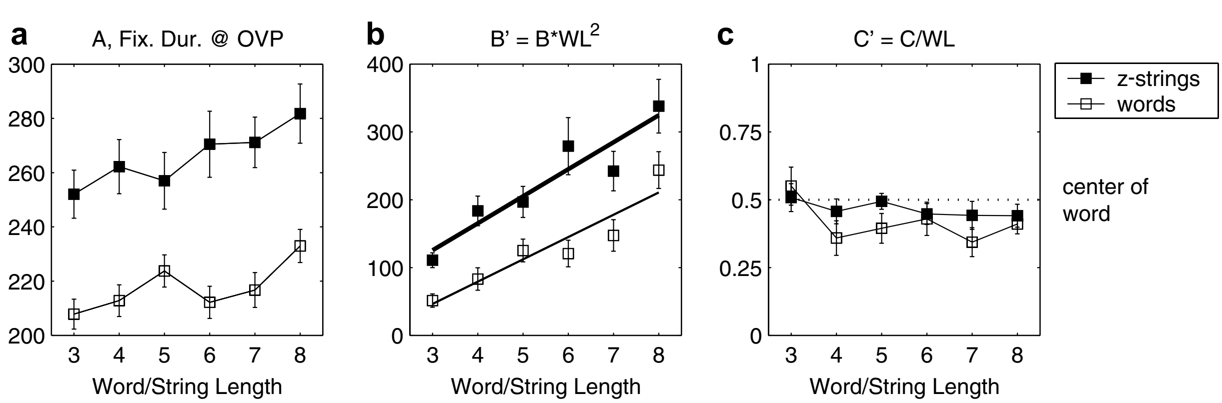


Fig. 4. IOVP effect for *z*-string reading data (full squares) vs. normal reading data (open squares). Empirical data were fitted to $y = A - B(x - C)^2$. Comparison of parameters of the quadratic function. Vertical bars represent standard errors of the means.

Table 2
Estimates of parameters $A$, $B'$, $CC$ and $C'$ for quadratic fixation-duration IOVP curves for $z$-string reading and normal reading

| Word length | Center of word | $z$-string reading | | | | | Normal reading | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A$ | $B'$ | $CC$ | $C'$ | $\chi^2$ | $A$ | $B'$ | $CC$ | $C'$ | $\chi^2$ |
| 3 | 2 | 252 | −111 | −0.48 | 0.51 | 361.23 | 208 | −51 | −0.35 | 0.55 | 246.47 |
| 4 | 2.5 | 262 | −184 | −0.67 | 0.46 | 1517.19 | 213 | −83 | −1.06 | 0.36 | 1057.6 |
| 5 | 3 | 257 | −197 | −0.53 | 0.49 | 1572.19 | 224 | −125 | −1.03 | 0.39 | 1653.38 |
| 6 | 3.5 | 270 | −279 | −0.81 | 0.45 | 4946.14 | 212 | −121 | −0.92 | 0.43 | 2181.67 |
| 7 | 4 | 271 | −242 | −0.9 | 0.44 | 6369.78 | 217 | −147 | −1.59 | 0.34 | 4256.15 |
| 8 | 4.5 | 282 | −338 | −0.97 | 0.44 | 18,650.1 | 233 | −244 | −1.21 | 0.41 | 8918.79 |

*Note.* $CC = C$—center of word. $\chi^2$ denotes sum of squared residuals.

significant word length effects for parameters $A$ and $B'$ ($A$: $F(5,21) = 11.43$, $MSe = 592$, $p = .000$, $B'$: $F(5,21) = 22.38$, $MSe = 14468$, $p = .000$). Finally, for parameter $A$ the word length effect was stronger in $z$-string than in normal reading (experimental condition × word length interaction: $F(5,21) = 2.67$, $MSe = 492$, $p = .040$). Taken together, the IOVP effect is stronger in $z$-string than in normal reading, as reflected in parameter $B'$. The results for $z$-strings are inconsistent with earlier research (Rayner & Fischer, 1996). The authors observed a significant effect of landing zone on single fixation duration for words, but not for $z$-strings (but see their Fig. 7 indicating considerable IOVP effects for 6- and 7-letter $z$-strings).

### 3.4. Modeling the IOVP effect for z-string reading

In previous work (Nuthmann et al., 2005) we suggested that the fixation-duration IOVP effect is a consequence of immediately started, potentially corrective, saccade programs in response to mislocated fixations caused by saccade errors. The existence of an IOVP effect in $z$-string reading, i.e., in the absence of word recognition, is qualitatively highly compatible with this notion. As a further test, we checked the quantitative agreement between our IOVP-generating algorithm and experimental data.

#### 3.4.1. Estimation of the proportion of mislocated fixations from empirical data

Landing position distributions are relatively broad with a mean slightly left of word center (cf., Fig. 2). It is a widely accepted view that this preferred viewing location (Rayner, 1979) is due to systematic and random error in the visuomotor system (McConkie et al., 1988). These oculomotor errors have two consequences. First, errors produce undershoots and overshoots of word centers of intended target words, causing the spread of within-word landing position distributions. More interestingly, oculomotor errors also lead to mislocalized fixations, that is fixations that land on a different than the intended word. Thus, words are also fixated, refixated, or skipped due to oculomotor error (see Engbert et al., 2007, for a classification of mislocated fixations and numerical simulations of the SWIFT model).

We do not know the intended target word for a specific saccade; only the *realized* but not the *intended* saccade amplitude can be measured experimentally. We developed, however, an algorithm for the estimation of the proportion of mislocated fixations from empirical data (Nuthmann et al., 2005) and validated this algorithm with simulations using the SWIFT model (Engbert et al., 2005). Landing position curves are normal curves truncated at word boundaries (cf., Fig. 2). We assumed that the tails of the (fitted) normal distributions (that overlap to adjacent words) represent mislocated fixations. To calculate the probability for mislocated fixations for normal vs. $z$-string reading, we employed a triplet-based algorithm considering the overlap of landing position distributions to neighboring words and/or $z$-strings. Every word, except the first and the last word of a given sentence, formed the center of a triplet representing three successive words, for example the word 'eine' [a] from the triplet 'wartete eine Kutsche' (waited a carriage) in Fig. 5. For the center word or corresponding $z$-string of every triplet, the overlaps from the left and right words were computed. Based on these overlap values, the proportion of mislocated fixations was computed as a function of word/string length and landing position (for details see Nuthmann et al., 2005). For different word lengths, the proportion of mislocated fixations increases with the (within-word) distance of the fixation location from word center (Fig. 6). The high similarity of landing position distributions for $z$-string and normal reading implies a high simi-

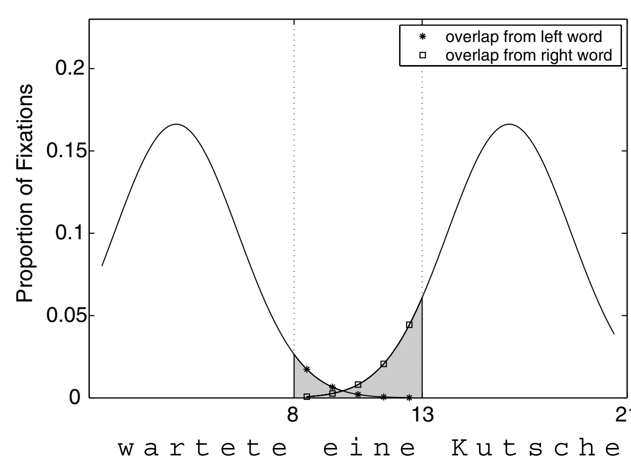


Fig. 5. Estimation of the proportion of mislocated fixations as a function of both word/string length and landing position; procedure illustrated with an example triplet from the normal reading condition.

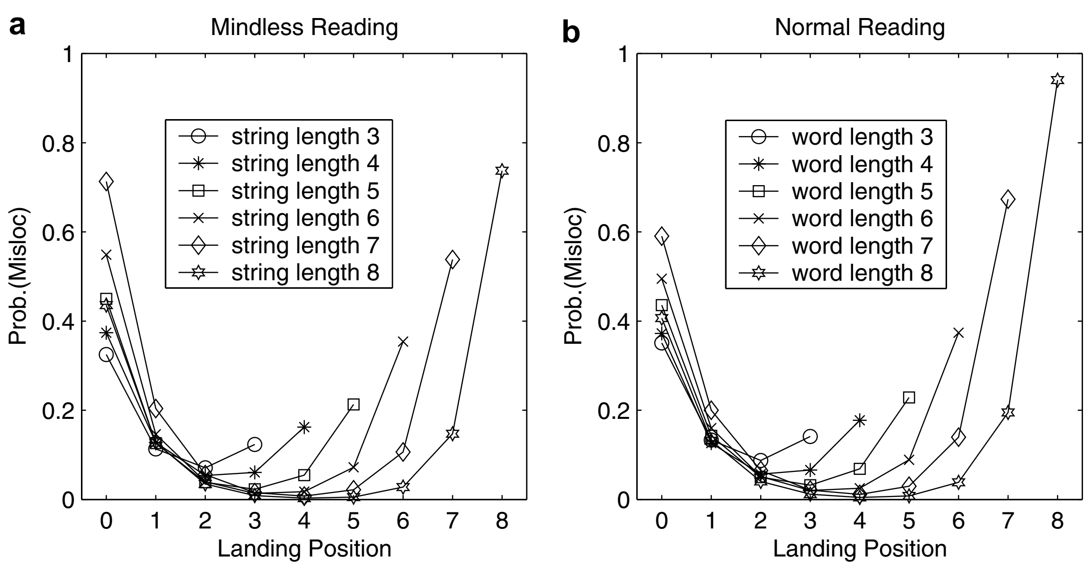


Fig. 6. Proportion of mislocated fixations as a function of word/string length and landing position, for *z*-string reading data (a) vs. normal reading data (b).

larity of corresponding estimated proportions of mislocated fixations (see Figs. 2 and 6).

*3.4.2. IOVP effects as a consequence of mislocated fixations*

We suggested that the oculomotor system responds to the mislocated fixation with the immediate start of a new, potentially error-correcting saccade program (Nuthmann et al., 2005). The immediate start of a new saccade program leads to shorter durations for mislocated fixations, if a substantial proportion of saccade programs is initiated after the beginning of the current fixation. Since mislocated fixations are more frequent at the beginning and end of words, we obtain an inverted U-shaped relationship for fixation duration as a function of landing position.

In the following, a quantitative check of this prediction is performed. For simplicity, it is assumed that the fixation durations $F_L$ for words/*z*-strings of length $L$ are independent of landing position without error-correction. Applying the proposed mechanism of error-correction of mislocated fixations, the resulting corrected fixation duration is formulated as

$$F_L^C(x) = F_L(1 - p_L^{\text{mis}}(x)) + \tau_C p_L^{\text{mis}}(x)$$
$$= F_L - (F_L - \tau_C)p_L^{\text{mis}}(x), \quad (2)$$

where $p_L^{\text{mis}}(x)$ denotes the probability for mislocated fixations on a word and/or *z*-string of length $L$ at letter position $x$ and $\tau_C$ is the latency of the error-correcting saccade program. According to Eq. (2), shape and size of the IOVP effect are determined by $p_L^{\text{mis}}(x)$ and $\Delta = F_L - \tau_C$. For the computations presented in Figs. 7b and d, a value of $\tau_C = 125$ ms was used.[1] The unknown value of $F_L$ was chosen in such a way that the resulting mean value for $F_L^C(x)$, averaged across all landing positions, equaled the experimentally observed mean fixation duration for words/*z*-strings of length $L$.

As for normal reading, the simulated IOVP curves (Fig. 7d) were in good agreement with the experimental data (Fig. 7c). More importantly for the current paper, the empirical IOVP effect for *z*-string reading is qualitatively reproduced by the algorithm (Fig. 7b). Thus, the introduced IOVP generating algorithm is able to reproduce the large difference between *z*-string and normal reading data, despite the similarity of their landing position distributions and consequent similarity in the probability of mislocated fixations. Recall that the IOVP effect was reproduced according to Eq. (2). There, $F_L$ represents the mean fixation duration for a word and/or *z*-string of length $L$. Thus, $F_L$ reflects the empirical fixation durations which are shifted towards longer durations in *z*-string compared to normal reading. Parameter $\tau_C$, reflecting the fast responses to mislocated fixations, is assumed to be independent of reading condition. Because $\Delta = F_L - \tau_C$ is considerably higher in *z*-string than in normal reading, the IOVP algorithm indeed reproduces the strong fixation-duration IOVP effect obtained in the *z*-string reading condition. Generally, generated IOVP curves are too flat around word center because the estimated probabilities for mislocated fixations, computed from overlapping landing position distributions, are rather low for the center region of the word.

## 4. General discussion

Reading involves the coordination of several central perceptual, cognitive, and motor subsystems of the human body. The problem of how these different processes interact

[1] Note that an IOVP effect is generated as long as $F_L > \tau_C$, while both values are bound by the minimum time required to program a goal-directed saccade.

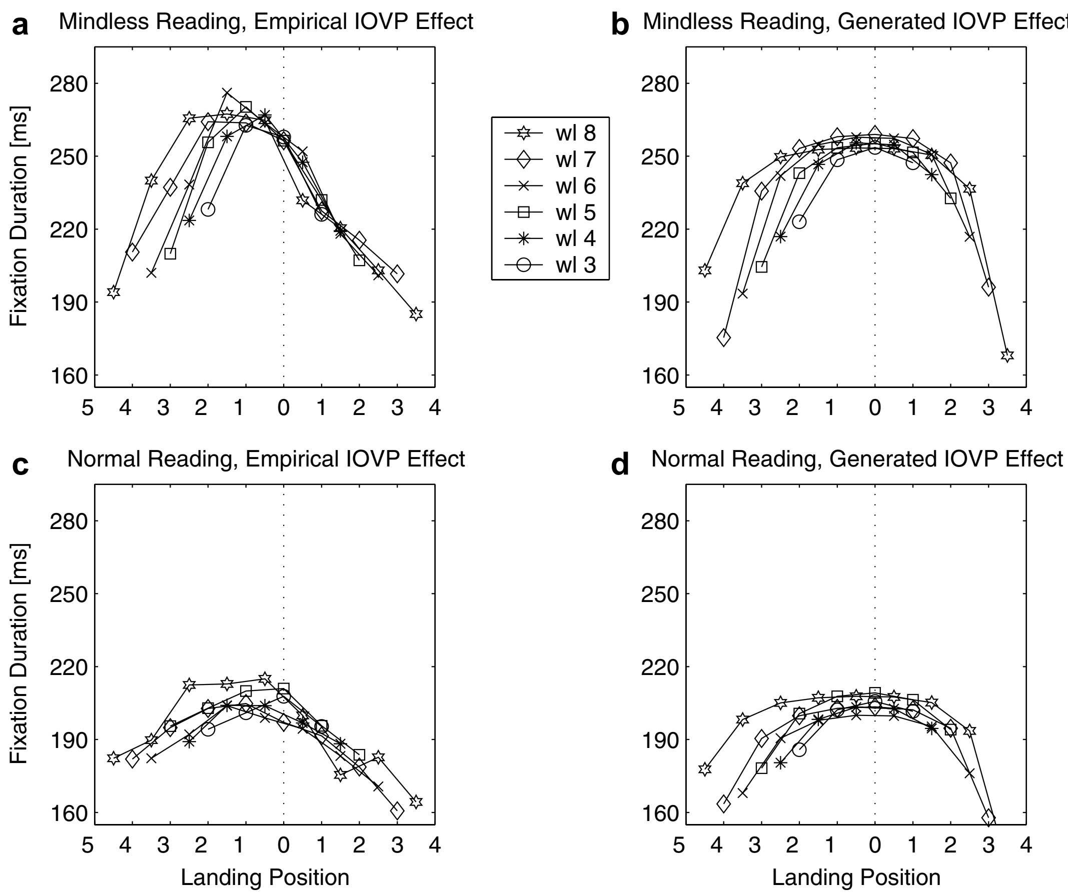


Fig. 7. Comparison of the empirical fixation-duration IOVP effect (left panels) with the generated IOVP effect (right panels), for *z*-string reading data (a and b) vs. normal reading data (c and d).

is crucial for advancing our understanding of reading. In this respect, the IOVP effect is a highly relevant phenomenon, since the results from mindless reading presented here suggest that the IOVP effect is related to at least four different processes: (a) saccade target selection, (b) generation of mislocated fixations due to systematic and random errors of saccades, (c) detection of mislocated fixations (via efference copy), and (d) initiation of an error-correcting saccade program. Interestingly, word recognition (as one of the key processes related to the function of eye movements in reading) seems not to be involved in the set of IOVP-generating mechanisms. The present findings support our earlier studies on the IOVP effect based on a data-driven algorithm for the computation of probabilities for mislocated fixations (Nuthmann et al., 2005), SWIFT simulations (Engbert et al., 2005) or a combination of both approaches (Engbert et al., 2007).

The finding that fixation durations near word boundaries are considerably shorter than fixation durations close to word centers was extensively investigated by Vitu et al. (2001). The IOVP effect is intriguing, because—from our knowledge on isolated word recognition—the word center clearly represents the optimal location for efficient word processing. This is probably the most important reason why the existence of these IOVP effects has been controversial for some time (Rayner et al., 1996, Rayner, Pollatsek, & Reichle, 2003). By now, however, the IOVP effect is a well-established phenomenon in reading research (McDonald et al., 2005; Nuthmann et al., 2005).

We have shown that the IOVP effect may arise as a consequence of mislocated fixations, if we assume that (a) a new saccade program is immediately started, whenever an intended word is missed and that (b) mislocated fixation locations are more likely to be found at the beginning and end of words. Our explanation relies on low-level perceptual-oculomotor mechanisms unrelated to word recognition and was implemented and validated with the SWIFT model (Engbert et al., 2005; Engbert et al., 2007). IOVP effects in *z*-string reading, conceptualized as an oculomotor control condition to normal reading, are compatible with this notion. Indeed, the IOVP effect was even stronger in *z*-string than in normal reading, as reflected in the slope (i.e., parameter $B'$) of the quadratic function. The proposed IOVP model qualitatively reproduced the strong IOVP effect in *z*-string reading.

### 4.1. Alternative accounts of the IOVP effect

Currently, there are several alternative hypotheses about the IOVP effect, two of them originating from experimental work and two of them from computational models. They will be discussed with respect to the present data.

#### *4.1.1. Perceptual economy processes*

Perceptual-economy processes are said to favor longer fixation durations at positions where greater amounts of information are anticipated (Vitu et al., 2001). If the IOVP effect depends on informative content in the reading material, then the perceptual-economy account would not specifically predict an IOVP effect in *z*-string reading because there is nothing to anticipate. This prediction presumes, however, that readers always deploy the most efficient reading strategy. It is not at all clear and rather doubtful that well-practiced readers can switch off their normal reading habits on demand. *Z*-string reading is a novel reading situation and it may require time for the system to calibrate itself to the non-informative reading situation. In addition, in the present study *z*-string trials were randomly mixed with 36 normal sentences which might have reduced the probability of such an adjustment.[2] As a consequence, finding no IOVP effect in *z*-string reading, a reduced IOVP effect or an IOVP effect showing a similar size in *z*-string reading and normal reading would be compatible with the perceptual-economy account. What we empirically find, however, is an IOVP effect that is significantly stronger in the *z*-string reading condition. This finding is not compatible with the perceptual economy account. Therefore, we conclude that perceptual-economy processes are not the *only* determinant of the IOVP effect. As shown with the present paper as well as other work (Nuthmann, 2006), the three parameters of the IOVP function are sensitive to experimental manipulations and differ between individuals. It remains to be seen whether the perceptual-economy account can handle these patterns. As a first step in this direction, the perceptual-economy account and its criteria of optimality need to be quantified and ideally implemented in a computational model. Such simulations could test whether or under what conditions it is indeed an optimal strategy to fixate longer at the center of words.

#### *4.1.2. Visuo-motor hypothesis*

In addition, Vitu et al. (2001) outlined three visuo-motor explanations for the IOVP effect, based on the idea that it takes longer to initiate a saccade from the center of a word as compared to word edges. Potentially, such a mechanism could also apply to *z*-string reading. Given that short saccade amplitudes take longer to program than medium-long amplitudes (cf., Kalesnykas & Hallett, 1994), the IOVP effect could arise if the length of saccades leaving the center of a word was smaller than the length of saccades leaving one of the word's ends. However, the empirical data did not support the saccade-length explanation (Vitu et al., 2001). Two other alternative explanations (disengaging a fixation and/or estimating the eyes' position might take longer when the eyes are at word center) could not be tested with their data. Vitu, Lancelin, Jean, and Farioli (2006) report slightly larger saccade latencies (about 13 ms) when the eyes move from a starting point with three to six letters adjacent to the fixated letter in comparison to a saccade from an isolated letter. This mimics the right wing of an IOVP curve for the case of well-located fixations. The size of the effect is, however, considerably smaller than the IOVP effect we observe in normal and *z*-string reading.

#### *4.1.3. SERIF*

In the SERIF model, a lateral inhibition mechanism, combined with the notion of an independent computation of information content in the two hemifields is responsible for the IOVP effect (McDonald et al., 2005). Fixation durations generated by SERIF are modulated by word frequency as well as the informativeness of the letter sequence. In *z*-string reading, however, there is no frequency effect on fixation durations, and the notion of information content does not apply. Therefore, the SERIF model predicts a considerably reduced IOVP effect for *z*-strings compared to the effect size for words. Our data do not support this prediction.

#### *4.1.4. E-Z Reader*

The word-recognition assumptions in the E-Z Reader model predict a U-shaped relation for fixation durations as a function of landing position (see Nuthmann et al., 2005). The most recent version of the model, however, is able to reproduce one specific IOVP effect (Pollatsek et al., 2006): As a result of the implementation of saccade programming in refixation cases, an IOVP effect for the first of two fixations emerges. It is, however, the IOVP effect for *single* fixations that is under theoretical debate because neither oculomotor nor cognitive models of eye-movement control in reading predict this effect *generically*. More important to the explanation favored by Pollatsek et al. (2006), however, is the fact that the IOVP-generating mechanism in E-Z Reader is based on word processing, which is obviously absent in *z*-string reading. Thus, the E-Z Reader model is not compatible with the present data.

#### *4.1.5. SWIFT*

The IOVP explanation advanced in Nuthmann et al. (2005) was implemented in the SWIFT model (Engbert et al., 2005). We assume (a) that reading saccades are directed to a specific target word, (b) that mislocated fixations are identified, and (c) that a potentially error-correcting saccade program is started immediately. The first assumption holds for cognitive models (e.g., Engbert et al., 2005; Reichle et al., 2003) and most oculomotor models (e.g., O'Regan, 1990; O'Regan & Lévy-Schoen, 1987; oculomotor word-targeting strategies in Reilly & O'Regan (1998); but see Yang & McConkie, 2004; Vitu, 2003, for a different perspective). In contrast, in the E-Z Reader model (Pollatsek et al., 2006) as well as in the

[2] Recall, however, that presentation order (randomized vs. blocked) did not affect mean fixation durations on *z*-strings in a study by Rayner and Fischer (1996).

SERIF model (McDonald et al., 2005), the mechanisms responsible for generating a fixation-duration IOVP effect are related to assumptions specific to the respective model. Finally, in principle, our proposed mechanism for the IOVP effect could be adopted by other computational models.

### 4.2. Limitations of the proposed IOVP model

Numerical simulations of the SWIFT model showed that the correction mechanism for mislocated fixations was able to reproduce the IOVP effect for single fixations (Engbert et al., 2005, see Fig. B1 with an incremental model analysis). To reproduce the IOVP effect for the first of multiple fixations as well as the fixation duration trade-off effect for two-fixation cases, however, we introduced an additional principle of saccade-latency modulation (Adams, Wood, & Carpenter, 2000; Kalesnykas & Hallett, 1994; Wyman & Steinman, 1973). Therefore, mislocated fixations might be a key factor driving the IOVP effect, but not an exclusive source.

In addition, our proposed IOVP model cannot account for an IOVP effect for first fixation durations in two-fixation cases, obtained in an isolated-word presentation paradigm (O'Regan & Lévy-Schoen, 1987). In this paradigm, the initial fixation location in the word is artificially imposed. After fixating a marker, the word appears, and sub-optimal landing positions may be corrected by refixation saccades. Consequently, mislocated fixations (as defined relative to an intended target word) cannot occur. We suggest that in the much more controlled paradigm of isolated word recognition a more precise error-correction mechanism might be at work. A possible error correction mechanism in isolated word recognition might respond to small deviations from word center. At the same time, such a more rigorous error correction may be absent in normal reading, because it would generate an error-correcting saccade during each fixation – a paradoxical situation for a task in which we impatiently try to move our eyes forward. Thus, a *minimal assumption* for the IOVP effect in reading is that oculomotor errors on the level of mislocated fixations are corrected, whereas small within-word deviations from word center remain uncorrected. In contrast, in isolated word recognition the eye-movement control system may respond even to small within-word errors in fixation location. Thus, even if the IOVP effect for the first of multiple fixations is found in both continuous reading as well as in isolated word presentation, the underlying neuro-cognitive mechanisms responsible for the effect are probably very different with respect to the role of visual feedback. In continuous reading, saccadic errors—frequently leading to mislocated fixations—are due to the inaccuracy of the oculomotor plant. Therefore, it is possible that the oculomotor system can predict these errors. In isolated word presentation, however, within-word errors are experimentally imposed eye deviations with respect to the center of the word. Consequently, these errors are usually not predictable and their correction requires visual feedback; they can only be corrected during the initial fixation taking the "eye-to-brain" lag (about 50 ms, e.g. Foxe & Simpson, 2002) into account.

### 4.3. Coding of saccade errors

With our mislocation explanation we assume a fast detection of saccade errors via efference copy. There is neurophysiological evidence suggesting that activity in the superior colliculus encodes the error between the intended saccade goal and the current gaze position (cf., Bergeron et al., 2003). The precise nature of such error encoding in reading is unclear. Word units are essential for eye-movement control in reading. Therefore, the coding of gaze error information is probably tied to the intended target word. Alternatively, the absolute size of the saccade error might be encoded. In exploratory simulations with the SWIFT model, the absolute saccade error sufficed to reproduce the IOVP effect qualitatively. This is possible via the correlation between the magnitude of saccade error and the probability of missing the intended target word. We will pursue this alternative once convincing evidence is available that information on whether the executed saccade landed on the intended target word is not available immediately following saccade offset.

### 4.4. Mindless reading paradigm

Mindless reading, operationalized as *z*-string scanning, is a valuable control task for research on reading. Many oculomotor phenomena known from reading are present, while word processing as one of the main forces driving eye movements in reading, is missing (Rayner & Fischer, 1996). Most importantly for the present study, the IOVP effect turned out not to be limited to reading. Indeed, one of the key motivations for our current investigation was to look for an IOVP effect in a non-reading task. Earlier, it has been reported that initial landing position affected first fixation duration in a visual-search-like task: Fixation duration decreased with the distance of the landing position from the center of the visual object (Henderson, 1993).

Interestingly, the inflated average fixation durations in *z*-string scanning are comparable to fixation durations in visual search tasks (Rayner, 1998, Table 1: visual search: 275 ms, silent reading: 225 ms; see also Trukenbrod & Engbert, submitted for publication). This variation in average fixation duration provides an interesting test of our IOVP model. Our theoretical model suggests that the effect increases with average fixation duration, since the effect size is given by $\Delta = F_L - \tau_C$, Eq. (2), where $F_L$ is the average fixation duration and $\tau_C$ is the programming time of the error-correcting saccade. Given that $\tau_C$ is a basic oculomotor parameter, it should be independent of the task. In our model, an increase of the average fixation duration $F_L$ predicts an increase of the IOVP effect size $\Delta$. Thus, our finding that the IOVP effect is greater in *z*-string scanning than in normal reading supports the assumptions of our IOVP model.

It is unclear what participants really do when asked to mimic reading in a *z*-string scanning task. One possible explanation for the prolonged fixation durations in *z*-string scanning is that participants simply overestimate the time they spend at each fixation during normal reading (Vitu et al., 1995). However, participants are generally unaware of saccades. Given the complexity of scan paths during normal reading (with refixations, skippings, and regressions), it is also questionable whether participants have good knowledge of their own attentional scanning rate.

The *z*-string reading paradigm is an informative oculomotor control condition to normal reading. The paradigm is termed "mindless reading", but it does not actually capture the phenomenon of mind-wandering in reading, i.e., the common experience of moving the eyes across text while the mind is elsewhere (cf., Schooler, Reichle, & Halpern, 2004). In perspective, it would be beneficial to develop experimental paradigms allowing to investigate whether and how mind-wandering episodes during reading affect measures of eye-movement control. This research may shed further light on the nature of the "eye-mind" link.

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